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Review of solar sorption refrigeration technologies: Development and applications

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Abstract

In this paper, a review of the research state of art of the solar sorption (absorption and adsorption) refrigeration technologies is presented. After an introduction of basic principles, the development history and recent progress in solar sorption refrigeration technologies are reported. The application areas of these technologies are categorized by cooling temperature demand. It shows that solar-powered sorption refrigeration technologies are attractive alternatives that not only can serve the needs for air-conditioning, refrigeration, ice making and congelation purposes, but also can meet demand for energy conservation and environment protection. However, a lot of research work still needs to be done for large-scale applications in industry and for the replacement of conventional refrigeration machines.

Keywords: Absorption; Adsorption; Solar-powered; Refrigeration; Coefficient of performance (COP)

Contents

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1. Introduction

The production of cold has applications in a considerable number of fields of human life, for example the food processing field, the air-conditioning sector, and the conservation of pharmaceutical products, etc. The conventional refrigeration cycles driven by traditional vapor compression in general contribute significantly in an opposite way to the concept of sustainable development. Two major problems have yet to be addressed:

- *The global increasing consumption of limited primary energy*: The traditional refrigeration cycles are driven by electricity or heat, which strongly increases the consumption of electricity and fossil energy. The International Institute of Refrigeration in Paris (IIF/IIR) has estimated that approximately 15% of all the electricity produced in the whole world is employed for refrigeration and air-conditioning processes of various kinds, and the energy consumption for air-conditioning systems has recently been estimated to 45% of the whole households and commercial buildings [1,2]. Moreover, peak electricity demand during summer is being re-enforced by the propagation of air-conditioning appliances.
- *The refrigerants used cause serious environmental problems*: The traditional commercial, non-natural working fluids, like the chlorofluocarbures (CFCs), the hydrochlorofluorocarbures (HCFCs) and the hydrofluocarbures (HFCs) result in both ozone depletion and/or global warming. Since the protocol of Montreal in 1987, international agreements have been signed to reduce the emissions of these refrigerants [3]. European Commission Regulation 2037/2000, which has been implemented on 1 October 2000, treats the whole spectrum of control and phase-out schedule of all the ozone depleting substances. It is indicated that till 2015 all HCFCs will be banned for servicing and maintaining existing systems [4].

During recent years research aimed at the development of technologies that can offer reductions in energy consumption, peak electrical demand and energy costs without lowering the desired level of comfort conditions has intensified [5]. By reason that solar refrigeration technologies have the advantage of removing the majority of harmful effects of traditional refrigeration machines and that the peaks of requirements in cold coincide most of the time with the availability of the solar radiation, the development of solar refrigeration technologies became the worldwide focal point for concern again.

Solar energy can be transformed either to electricity or to heat to power a refrigeration cycle. During the past decade, since the efficiency of the solar photovoltaic collectors increases only slightly (10–15%) contrary to that of the solar thermal collectors, and the electrically driven systems are characterized by the limited useful power that can be achieved by solar means, and also by their fairly high initial cost [6,7], more interests have

been paid to the solar thermal-driven refrigeration technologies, especially solar sorption (absorption and adsorption) systems. In this paper, an overview of the principles of solar sorption refrigeration technologies will be given and the development and applications of these systems will be discussed in later sections.

2. Description of solar sorption refrigeration technologies

The existing systems for producing cold using solar thermal energy are based mainly on the phenomena of sorption: the process by absorption liquid–gas and the process by adsorption solid–gas. The adsorption process concerns separation of a substance from one phase, accompanied by its accumulation or concentration on the surface of another. On the other hand, absorption is the process in which material transferred from one phase to another, (e.g. liquid) interpenetrates the second phase to form a solution. In general, the main differences between absorption and adsorption are located in the nature of the sorbent and the duration of the sorption cycle, which is significantly longer for adsorption [6].

Two key figures describing the efficiency of a solar sorption refrigeration system are thermal coefficient of performance (COP) and solar COP, which are defined as follows:

$$\mathrm{COP_{thermal}} = \frac{\text{cooling power}}{\text{energy received by system}},$$

$$\mathrm{COP_{solar}} = \frac{\text{cooling power}}{\text{energy received by solar collector}}.$$

It is obvious that the calculation of solar COP includes the solar collector efficiency, for this reason it is much weaker than thermal COP.

2.1. Absorption

The phenomenon of absorption is the mixture of a gas in a liquid, the two fluids presenting a strong affinity, to form a solution [8]. This process is reversible. One can describe the principle of a simple effect system with H_2O–LiBr as working pair (Fig. 1).

1. A pump brings the rich solution towards the high-pressure zone.
2. The mixture is heated in the generator. A contribution of heat (waste heat, solar energy) allows the separation of the refrigerant (H_2O) from the absorbent (LiBr solution).
3. The vapors of refrigerant are sent towards the traditional cycle of condenser, expansion valve and evaporator. Cold is produced by the evaporation of refrigerant in the evaporator at low pressures.
4. The poor solution turns over in the absorber by passing by a pressure-relief valve.
5. The vapors of refrigerant are absorbed by the poor solution of absorber coming from the generator. The cycle can start again.

The majority of absorption systems are single effect, with the solar flat-plate collectors at low temperatures. Recent researches show that there are also double-effect systems, available on the market, with thermal COP in the range of 1.0–1.2, and triple-effect systems with thermal COP of 1.7 (Fig. 2). Multi-effect absorption systems require higher

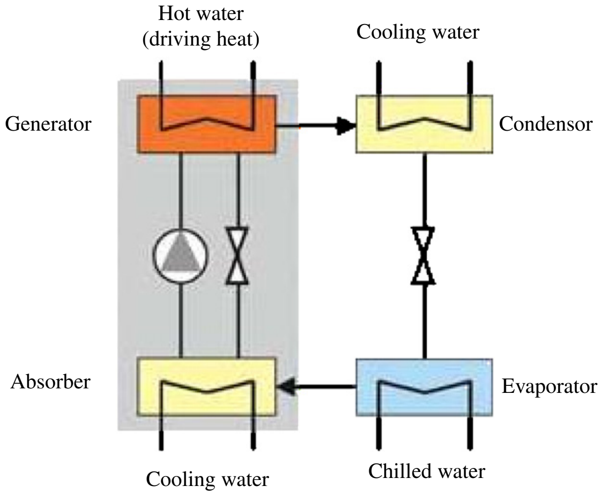

Fig. 1. Schematic drawing of an absorption chiller [60].

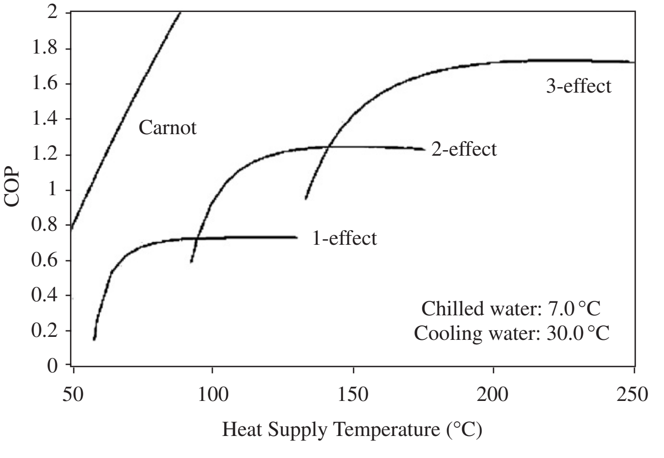

Fig. 2. COP as a function of solar heat supply temperature for single-, double- and triple-effect H_2O–LiBr absorption chillers [9].

heat supply temperatures, which may be obtained from higher-cost concentrating or evacuated tube collectors.

After an economic comparison, Grossman [9] concluded that the total system cost would be dominated by the solar part of the system. Meanwhile, Sumathy et al. [10] also developed a new model of two-stage H_2O–LiBr absorption chiller. Test results have proved that the two-stage chiller could be driven by low temperature hot water ranging from 60 to 75 °C, which can be easily provided by conventional solar hot water systems. Compared to the single-stage chiller, the two-stage chiller could achieve roughly the same total COP as of the conventional system with a cost reduction of about 50%.

Table 1
Comparison between the absorption systems with NH_3–H_2O and H_2O–LiBr

Working pair	Advantages	Disadvantages
NH_3–H_2O	Evaporative at the temperatures below 0 °C	Toxic and dangerous for health (ammonia)
		In need of a column of rectifier
		Operation at high pressure
H_2O–LiBr	High COP	The risk of congelation, therefore a device anti-crystallization is necessary
	Low operation pressures	Relatively expensive (LiBr)
	Environmental friendly and innoxious	
	Large latent heat of vaporization	

Two major working pairs used in the solar absorption refrigeration systems are H_2O–LiBr and NH_3–H_2O. H_2O is refrigerant and LiBr is absorbent in the former system, oppositely NH_3 is refrigerant and H_2O is absorbent in the latter case. Each working pair has its advantages and disadvantages, as shown in Table 1. Broadly speaking, NH_3–H_2O systems are often used for refrigeration and in industrial applications while H_2O–LiBr systems are more suitable for air-conditioning purposes.

Other working pairs also have been investigated. In Denmark, Worsøe-Schmidt [11] in 1979 developed a solar-powered solid-absorption refrigeration system with NH_3–$CaCl_2$ and $SrCl_2$ as working pairs. The experimental investigation showed an overall COP of 0.10, corresponding to an ice production of 6 kg/m^2 of collector area. Similar work has also been done by Erhard and Hahne [12] in a solar cooling machine for demonstration purposes, with NH_3 and $SrCl_2$ as working pair. The overall COP of the cooling system has been calculated as 0.049, using data of 1994. In 1995, a better overall COP (0.045–0.082) was attained.

Bansal et al. [13] reported a unit of 1.5 kWh/day using NH_3 as refrigerant and IMPEX material (80% $SrCl_2$ and 20% Graphite) as absorbent. Theoretical maximum overall COP of the unit is 0.143, and it depends upon the climatic conditions.

Medrano et al. [14] discussed the potential of using organic fluid mixtures trifluoroethanol (TFE)–tetraethylenglycol dimethylether (TEGDME or E181) and methanol–TEGDME as working pairs in series flow and vapour exchange double-lift absorption cycles. The simulation results showed that the COP of the vapor exchange cycle working with TFE–TEGDME is 15% higher than that with NH_3–H_2O.

Romero et al. [15] employed an aqueous ternary hydroxide working fluid which consisted of sodium, potassium and cesium hydroxides in the proportions 40:36:24 (NaOH:KOH:CsOH) in a solar absorption cooling system. From the results obtained so far, it seems that the system with the hydroxide mixture might operate with higher COP than the system with the H_2O–LiBr mixture. It is also appears that the system with the hydroxide might operate with a broader range of temperatures.

In Mexico a theoretical study of an intermittent absorption refrigeration system has been done by C.O. Rivera and W. Rivera [16]. The designed system driven by a compound parabolic concentrator operated with $LiNO_3$ mixture in order to avoid a rectifier. The results showed that in a typical Mexico weather, it was possible to produce up to 11.8 kg of

ice and the thermal COPs were between 0.15 and 0.4 depending on the generation and condenser temperatures.

2.2. Adsorption

Adsorption is the general phenomenon resulting from the interaction between a solid (adsorbent) and a gas (refrigerant), based on a physical or chemical reaction process. An adsorption refrigeration machine utilizes the phenomenon of physical adsorption between the refrigerant and a solid adsorbent; the molecules of the refrigerant come to be fixed at the surface of adsorbent via connections of the type Van der Waals [17]. It is generally consisted of a generator, a condenser, a pressure-relief valve and an evaporator. The generator consists of a solar plate containing the adsorbent, which is heated by the solar radiation, for desorption of refrigerants. A structure example of this kind of system is illustrated in Fig. 3.

When fixed adsorbent beds are employed, which is the common practice, these cycles can be operated without any moving parts. On the one hand, the use of fixed beds results in silence, mechanical simplicity, high reliability and a very long lifetime, on the other hand, it also leads to intermittent cycle operation, with adsorbent beds changing between adsorption and desorption stages, which decreases the COP of the system. Hence, when constant flow of vapor from the evaporator is required in order to provide continuous cooling, two or more adsorbent beds must be operated out of phase [17].

Schema of a two beds continuous adsorption refrigeration system with heat recovery is shown in Fig. 4. When adsorber 1 is cooled and connected to the evaporator to get adsorption refrigeration in the evaporator, and adsorber 2 is heated and is connected to the condenser to get heating–desorption–condensation, the condensed refrigerant liquid flows into evaporator via a flow control valve [18].

Activated carbon, silicagel and zeolite are most widely used adsorbents while water, methanol (ethanol) or ammonia are most widely used adsorbates in solar-powered or

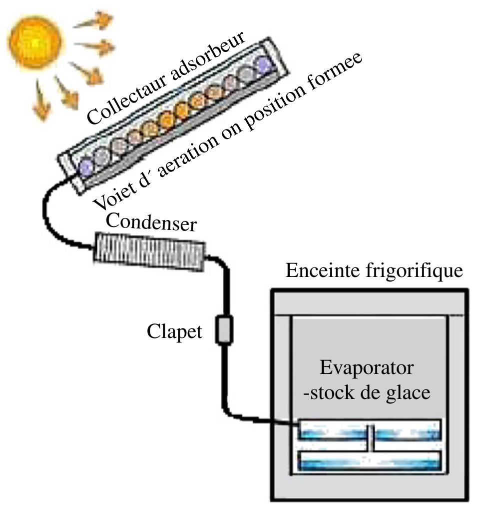

Fig. 3. Schematic drawing of a solar adsorption refrigerator [7].

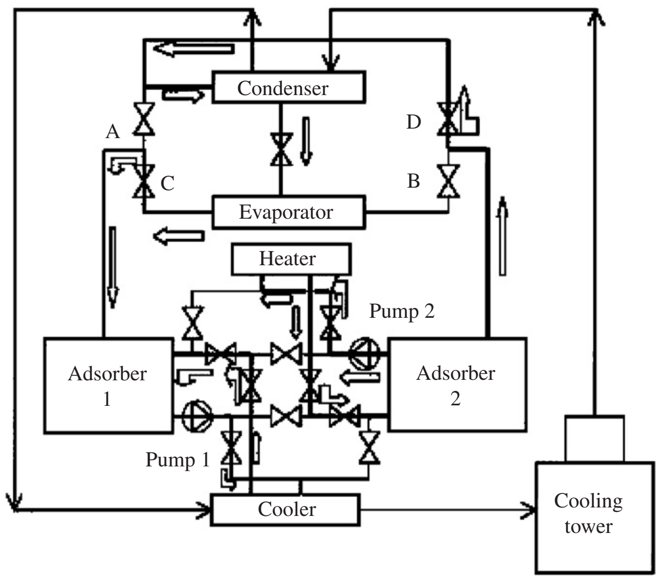

Fig. 4. Schematics of heat recovery two-beds adsorption refrigeration system [18].

waste heat-driven adsorption refrigeration systems. In order to choose the best working pair for a specific use, Luo et al. [19,20] summarized and compared 15 adsorbents (12 activated carbon, 3 zeolite), 4 adsorbates (methanol, ethanol, ammonia, water) under the same conditions, with cycle COP as the same criterion. The results show that methanol/activated carbon PICASOLV is the best among all the studied working pairs. A cycle COP of 0.55 could be achieved at evaporation and condensation temperatures of -5 and 30 °C, respectively. Recently, Anyanwu and Ogueke [21] compared thermodynamically the different systems using activated carbon/methanol, activated carbon/ammonia and zeolite/water adsorbent/adsorbate pairs. It was concluded that zeolite/water is the best pair for air conditioning application while activated carbon/ammonia is preferred for ice making, refrigeration and food preservation. The maximum possible net solar COP was found to be 0.3, 0.19 and 0.16 for zeolite/water, activated carbon/ammonia and activated carbon/methanol, respectively, when a conventional flat plate solar collector was used.

But from a practical standpoint, none of these working pairs are perfect. The principal limitation of these cycles lies in the weak mass and heat transfer characteristics of the adsorbent beds. The adsorbents, like the activated carbon, the zeolites or the silicagel have low thermal conductivities and poor porosity characteristics. The effect is the bulky collector/generator/adsorber component and, thus, its excessive heating capacity, leading to rather low thermal COP [22]. The above difficulty is a real challenge faced by researchers and much effort has been devoted to overcome this inconvenience. Munyebvu [23] produced activated carbon from monolithic discs housed in a tube with internal fins to improve both its thermal conductivity and thermal contact with metal elements. Li and Wang [24] detailedly analyzed both parametric effects of collector and environmental parametric effects on performances of solar-powered adsorption refrigerator. The author concluded that the heat transfer and thermal conductivity of the adsorbent beds could be

enhanced by adding packing density of adsorbent, adopting double glass covers, using selective coating material as well as using heat transfer fins. Moreover, choosing a suitable environmental condition may improve the performance of solar refrigerator.

Another effective way to enhance materials heat transfer properties is the use of consolidated adsorbent. A considerable amount of research has been focused on this field. Wang et al. [25] made a literature review on current progress of consolidated adsorbent for adsorption systems. A number of consolidated technologies of adsorbent were discussed. It is concluded that consolidated adsorbent materials have very good heat transfer properties, which provide new possibilities for compact adsorption machines.

3. Applications of solar sorption refrigeration systems

Based on the cooling temperature demand, the applications of solar sorption systems can be broadly classified into three categories: air-conditioning (8–15 °C) for spaces, refrigeration (0–8 °C) for food and vaccine storage, and freezing (<0 °C) for ice-making or congelation purposes. In this section, the development of solar sorption refrigeration systems is presented and researches currently in progress for different applications are also discussed.

3.1. Air-conditioning

An air-conditioning system is used to control temperature and humidity for indoor thermal comfort for people. The demand of this application is high in populated place such as a big city. The solar sorption refrigeration systems are suitable for air-conditioning due to the low installation cost and the high cooling capacity. In the 1960s, solar-powered absorption systems were considered to be used in the field of air-conditioning [26,27].

The first large-scale experiments for air-conditioning can be traced to 1970s. In 1976 around 500 solar-powered air-conditioning systems were installed in USA, most of which were absorption systems using LiBr [1]. Meantime in Japan, a solar heating and cooling system with flat-plate collectors and absorption refrigeration machine was installed [28].

Yeung et al. [29] designed and constructed a solar-powered absorption air-conditioning system to study the feasibility of utilizing solar power for comfort cooling in Hong Kong. The system consisted of a flat-plate collector array with a surface area of 38.2 m^2, a 4.7 kW nominal cooling capacity H_2O–LiBr absorption chiller, a 2.75 m^3 hot-water storage tank, a cooling tower, a fan-coil unit, an electrical auxiliary heater. It had an annual system efficiency of 7.8% and an average solar fraction of 55%.

Syeda et al. [30] studied solar cooling system for typical Spanish houses in Madrid. The system consisted of a flat-plate collector array with a surface area of 49.9 m^2, a 35 kW nominal cooling capacity single-effect (H_2O–LiBr) absorption chiller. This machine operated within the generation and absorption temperature ranges of 57–67 °C and 32–36 °C, respectively. The measured maximum instantaneous, daily average and period average COP were 0.60 (at maximum capacity), 0.42 and 0.34, respectively.

Assilzadeh et al. [31] presented a H_2O–LiBr absorption unit using evacuated tube solar collectors for Malaysia and similar tropical regions. After the modeling and simulation carried out with TRNSYS program, the author concluded that the optimum system for Malaysia's climate for a 3.5 kW system consists of 35 m^2 evacuated tubes solar collector sloped at 20°.

Presently Argiriou et al. [32] also developed a prototype of low capacity (10 kW) single stage H_2O–LiBr absorption heat pump, suitable for residential and small building applications.

In Europe, more close attention was paid to the research and application of solar-powered sorption systems for air-conditioning. The International Energy Agency (IEA) set up the "Solar Heating and Cooling" program in 1977, which is still active as of present (2005). Task 25 "Solar Assisted Air Conditioning of Buildings", which ended in 2004, focused on the use of solar energy for air-conditioning of buildings. The main objective of the task was to improve conditions for the market entry of solar-assisted cooling systems, mainly absorption and adsorption systems [33].

EU project SACE (Solar Air Conditioning in Europe), aimed to assess the state-of-the-art, future needs and overall prospects of solar cooling in Europe was reported recently. A group of researchers from five countries have surveyed and analyzed over 50 solar-powered cooling projects in different climatic zones. The results of the study, including a database of the surveyed projects, an evaluation of these projects on a uniform basis, an economic analysis tool, user guidelines and a multimedia tool—are presented. The potential energy savings and limitations of solar thermal air-conditioning in comparison to conventional technologies are illustrated and discussed [34].

In China, solar-powered sorption systems have been studied intensively during last several years. The institute of refrigeration and cryogenics in Shanghai Jiao Tong University developed and tested different kinds of prototypes for practical purposes: air-conditioning for bus and train locomotive. The systems are all adsorption refrigeration systems driven by solar or waste heat energies, with activated carbon–ammonia or zeolite–water as working pair. It was reported that an average continuous refrigeration power of about 4.1 kW was obtained, which is enough to make the driver's cab comfortable in a train locomotive [18,35]. Fig. 5 presents the schematic of this air-conditioner.

3.2. Refrigeration

The low temperature application like food and vaccine storage can also be used as sorption systems. As a matter of fact, these technologies are attractive for refrigeration purpose in remote or rural areas of developing countries where the access to electricity is impossible. Various kinds of solar sorption refrigerators have been developed.

Uppal et al. [36] built in 1986 a small capacity (56 l) solar-powered NH_3–H_2O absorption refrigerator to store vaccines in remote locations. In the same period, Staicovici [37] developed an intermittent single-stage solar absorption system for fish preservation. Actual thermal COP of 0.25–0.30 could be achieved at generation and condensation temperatures of 80 and 24.3 °C, respectively.

In 1993, Sierra et al. [38] used a solar pond to power an intermittent absorption refrigerator with NH_3–H_2O solution. It is reported that generation temperatures as high as 73 °C and evaporation temperatures as low as –2 °C could be obtained. The thermal COP working under such conditions was in the range of 0.24–0.28.

Critoph [17,39] studied a rapid cycling solar/biomass-powered adsorption refrigeration system with activated carbon–ammonia as working pair. The thermal COP was about 0.3 when the initial generator temperature was about 50 °C and evaporating temperature was about 0 °C.

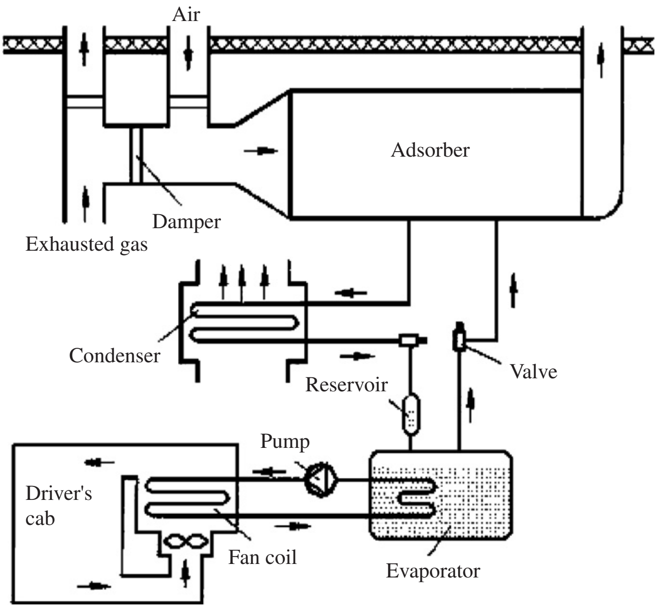

Fig. 5. Schematics of locomotive air-conditioner [35].

A commercially available low temperature (80–90 °C) adsorption cooling system for air-conditioning application has been modified, using methanol/silicagel as working pair for the cold storage of agricultural products at temperatures of 2–4 °C in India. Calculation and test results showed that the COP was about 0.30 when operating the system at a chilled water temperature of −2 °C, a heating water temperature of 85 °C and a condenser temperature of 30 °C [40].

Hammad and Habali [41] designed a solar-powered absorption refrigeration cycle using NH_3–H_2O solution to cool a vaccine cabinet in the Middle East. A year round simulation indicated that thermal COP ranged between 0.5 and 0.65 with generation temperature at 100–120 °C and the cabinet inside temperature at 0–8 °C.

In 2001, De Francisco et al. [42] developed and tested a prototype of 2 kW NH_3–H_2O absorption system in Madrid for solar-powered refrigeration in small rural operations. The test results showed unsatisfactory operation of the equipment with COP lower than 0.05.

Anyanwu and Ezekwe [43] also designed, constructed and tested a solid adsorption solar refrigerator using activated carbon–methanol as the working pair. Its flat-plate type collector/generator/adsorber used clear plane glass sheet whose effective exposed area was 1.2 m^2 with the efficiencies of 11.6–16.4%. The steel condenser tube with a square plan view was immersed in pool of stagnant water contained in a reinforced sandcrete tank. The evaporator is a spirally coiled copper tube immersed in stagnant water. Ambient temperatures during the adsorbate generation and adsorption process varied over 18.5–34 °C. The refrigerator yielded evaporator temperatures ranging over 1.0–8.5 °C from water initially in the temperature range 24–28 °C. Accordingly, the maximum daily useful cooling produced was 266.8 kJ/m^2 of collector area and the useful cycle and the useful overall COPs ranged over 0.056–0.093 and 0.007–0.015, respectively.

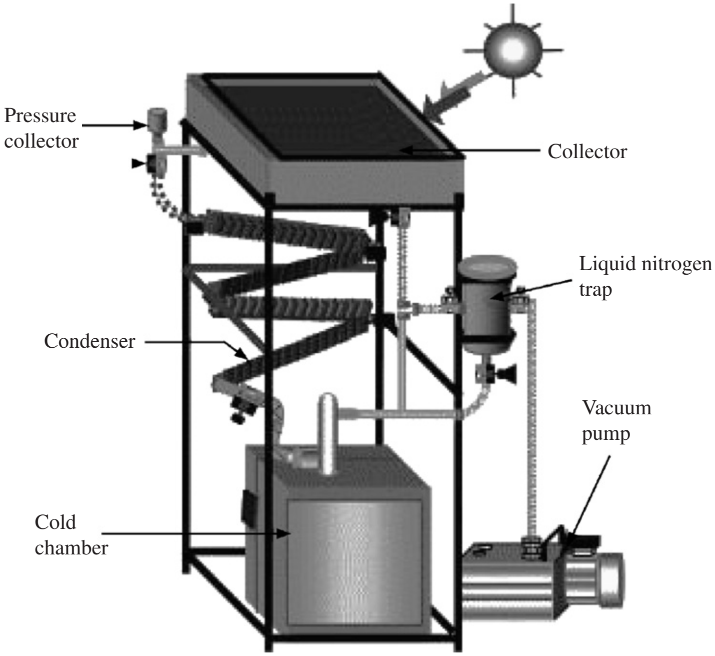

Fig. 6. Layout of the experimental unit of Lemmini and Errougani [46].

After the thermodynamic analysis of a monomethylamine/water single-stage absorption refrigeration cycle, Pilatowsky et al. [44,45] proposed evacuated tube collectors coupled with a conventional auxiliary heating system for milk cooling in the rural regions of Mexico. The results showed that it is possible to obtain evaporator temperatures from -5 to 10 °C at low generation temperatures from 60 to 80 °C, and condenser temperatures of 25 °C, obtaining thermal COP values from 0.15 to 0.7.

Lemmini and Errougani [46] built and tested a solar-powered adsorption refrigerator using the pair AC35–methanol in Rabat Morocco. The system consists of a flat-plate collector, a condenser and a cold chamber-evaporator. Experimental results showed that the unit can produce cold air even for rainy and cloudy days and the solar COP ranges between 0.05 and 0.08 for an irradiation between 12,000 and 27,000 kJ/m^2, a daily mean ambient temperature between 14 and 18 °C and lowest temperature achieved by the evaporator between –5 and 8 °C. The layout of the experimental unit is illustrated in Fig. 6.

3.3. Ice-making and congelation

For freezing application that needs temperature below 0 °C, like icemaker or congelation storage; an absorption chiller, an adsorption chiller, or a chemical reaction chiller can also be used. Generally speaking, the lower cooling temperatures demanded, the higher generation temperatures are needed for driving a sorption refrigeration system. One can list some typical achievements as follows.

Medini et al. [47] studied a non-valve solar adsorption ice maker with a 0.8 m^2 collection surface in 1991. The prototype employed an intermittent daily cycle with activated carbon AC35–methanol pair. The results showed that, with a collection efficiency of 0.41 and a thermal COP of 0.40, it is possible to obtain a gross solar COP of 0.15, and produced 4 kg of ice per day, during summer.

Critoph [48] built a small solid adsorption solar refrigerator in 1994. The collector is 1.4 m^2 in area and contains 17 kg of active carbon. The cold box is remote from the collector, being linked to it by a flexible steel hose. It is possible to produce up to 4 kg of ice per day in a diurnal cycle.

Sumathy and Li [49] operated a solar-powered ice-maker with the solid adsorption pair of activated carbon and methanol, using a flat-plate collector with an exposed area of 0.92 m^2. This system could produce ice of about 4–5 kg/day with a solar COP of about 0.1–0.12.

Khattab [50] developed a solar-powered adsorption refrigeration module with the solid adsorption pair of local domestic type charcoal and methanol. The module consists of a modified glass tube having a generator (sorption bed) at one end, a combined evaporator and condenser at the other end and simple arrangement of plane reflectors to heat the generator. Test results show that, the daily ice production is 6.9 and 9.4 kg/m^2 and net solar COP is 0.136 and 0.159 for cold and hot climate, respectively.

Hildbrand et al. [51] built and tested a new high-efficiency adsorptive solar refrigerator in Yverdon-les-Bains, Switzerland. The adsorption pair is silicagel–water. Cylindrical tubes function as both the adsorber system and the solar collector (flat-plate, 2 m^2 double glazed); the condenser is air-cooled (natural convection) and the evaporator contains 40 l of water that can freeze. This ice functions as a cold storage for the cabinet. This system has presented interesting performances, with a solar COP of 0.16.

A lot of research work on adsorption refrigeration has been done in Shanghai Jiao Tong University since 1993. Several prototype adsorption icemakers have been developed and tested in the past years. Li et al. [52] built a flat-plate solid-adsorption refrigeration ice maker with activated carbon–methanol as working pair for demonstration purposes. The experimental results show that the thermal COP is about 0.45 and solar COP is about 0.12–0.14, with approximately 5–6 kg of ice produced per m^2 collector. After some improvements, a similar no valve solar icemaker was built by Li et al. [53]. For this system, there are no any reservoirs, connecting valves or throttling valve, and the structure of the system is very simple. Fig. 7 gives the outline and the sketch structure of this prototype.

Experimental results showed that 6.0–7.0 kg ice can be obtained under indoor conditions when radiation energy was about 17–20 MJ/m^2, for these conditions, the solar COP of this system was about 0.13–0.15. In out door conditions, the system could produce 4.0 kg ice and the solar COP was about 0.12 when the total insolation energy was about 16–18 MJ/m^2. And then, a new solar ice maker developed can produce about ice of 4–5 kg each sunny day under the condition of about 18–22 MJ/m^2 solar insolation, with the price of no more than US $250 for per solar ice maker with 1 m^2 collector. These improved economic solar icemakers are now fabricated for mass application in China.

Though application of solar sorption refrigeration systems in the field of ice making has proliferated in recent years, effort in congelation, especially in low-temperature applications ($-18\,^{\circ}C$) is lacking. Wang [18] summed up an adsorption ice-making system driven by generation temperatures from 90 to 100 °C with activated carbon–methanol as working pair. This system can reach an evaporation temperature as low as $-15.5\,^{\circ}C$.

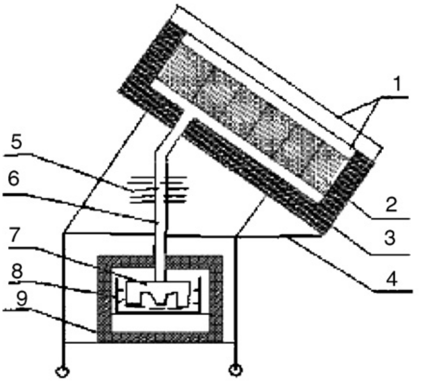

Fig. 7. The sketch structure of the no valve solar icemaker: (1) cover plate, (2) adsorbent bed, (3) insulation materials, (4) ice frame, (5) condenser, (6) connecting pipe, (7) evaporator, (8) water tank, (9) insulation box [35].

A prototype of a solid–gas adsorption processes with $BaCl_2$–ammonia chemical reaction and transformation liquid–gas of ammonia for congelation purpose has been constructed and tested in the laboratory PROMES in Perpignan, France. The experimental results proved that it is possible to produce cold with the temperatures less than $-20\,^{\circ}C$ and a minimal temperature of $-30.5\,^{\circ}C$ can be reached. The solar COP obtained is 0.061, which is comparable with the performances presented by other systems [54]. Their results may then serve as guidelines for producing low temperature cold by solar energy.

3.4. Combined systems

Recently, more close attention was paid to the development of combined systems of solar cooling and heating in order to make use of all types of energies rationally. All these works will be of great favor to the development of the solar sorption refrigeration system.

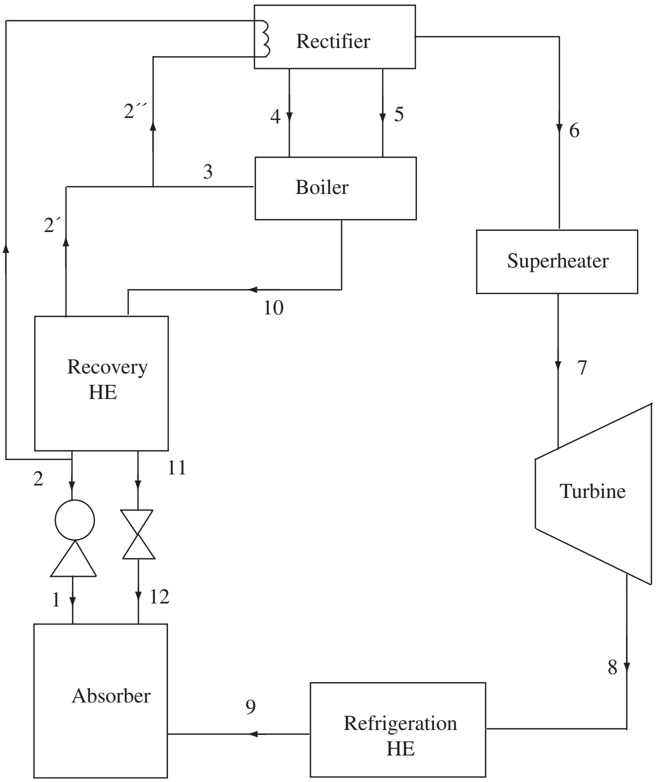

Fig. 8. Schematics of the power and cooling cycle.

Wang et al. [55,56] proposed a new solar-powered continuous solid adsorption refrigeration and heating hybrid system. By day the hybrid system of single combined bed could furnish 30 kg hot water of 47.8 °C, with a mean COP cooling of 0.18, a mean COP heating of 0.34, and by night it had a cooling capacity of 0.26 MJ/kg of adsorbent, and a cooling capacity of 1.3 MJ/m^2 of heat-collecting area.

Liu and Wang [57] studied a new kind of double effect H_2O–LiBr solar absorption system together with natural gas for air-conditioning, space heating and domestic hot water. Simulation results illustrated that this kind of system is feasible and economical.

In order to overcome the intermittent character of a single bed solar adsorption cycle, a novel model of the combined cycle of a solar-powered adsorption–ejection refrigeration system was established by Li et al. [58]. The estimated thermal COP is about 0.4 under the following operating conditions: condensing temperature 40 °C, evaporating temperature 10 °C, regenerating temperature 120 °C and desorbing temperature 200 °C, using zeolite 13X–water as the working pair.

Tamm et al. [59] proposed a system that combines the Rankine and absorption refrigeration cycles, using a binary ammonia–water mixture as the working fluid (Fig. 8). Results showed that the vapor generation and absorption condensation processes work experimentally. The potential for combined turbine work and refrigeration output was evident in operating the system.

Table 2
Comparison between solar-powered absorption and adsorption systems [1]

System	Advantages	Disadvantages
Absorption	Only one moving part (pump) with possibly no moving part for a small system	Low COP
	Low-temperature heat supply is possible	It cannot achieve a very low evaporating temperature The system is quite complicated
Adsorption	No moving part (except valve)	High weight and poor thermal conductivity of the adsorbent. For high capacity system, it can cause long-term problems
	Low operating temperature can be achieved	Low operating pressure requirement makes it difficult to achieve air-tightness
	Thermal COP is quite high compared to other heat operating systems	Very sensitive to low temperature especially the decreasing temperature during nighttime It is an intermittent system

4. Conclusion

In this paper, a review of the research state of the art of solar sorption (absorption and adsorption) refrigeration technologies is presented. From the discussion, one may conclude that solar-powered sorption refrigeration technologies could be used for producing a wide range of temperatures of cold. They are attractive technologies that not only can serve the needs for refrigeration, air-conditioning applications and ice making, but also can meet demand for energy conservation and environment protection. Comparatively, absorption systems are more suitable for air-conditioning while adsorption systems are more employed for low temperature purpose. The advantages and disadvantages of both systems are listed in the Table 2.

It should be noted that the applications of solar sorption systems are not limited to the above areas. There are many other applications, which are not described here either because they are not fully developed or are not matured yet. The field of studies is still vast.

But due to the relatively low COP or low energy conversion efficiency of solar collectors, currently most of the applications are in the stage of demonstration and prototyping. However, a lot of research work still needs to be done for enhancing the heat and mass transfer to improve performances of solar sorption refrigeration systems. More modern solar energy collecting and transferring technologies, and more advanced optimization and simulation models are also being anticipated. In addition, combined systems and domestic equipments using advanced micro-exchangers are also the trend of development.

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